

# Tracking & Data Relay Satellite Fault Isolation & Correction using PACES: Power & Attitude Control Expert System

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## ***Abstract***

*The Power and Attitude Control Expert System (PACES) is an object oriented and rule based expert system which provides spacecraft engineers with assistance in isolating and correcting problems within the Power and Attitude Control Subsystems of the Tracking and Data Relay Satellites (TDRS).*

*PACES is designed to act in a consultant role. It will not interface to telemetry data, thus preserving full operator control over spacecraft operations. The spacecraft engineer will input requested information. This information will include telemetry data, action being performed, problem characteristics, spectral characteristics, and judgments of spacecraft functioning.*

*Questions are answered either by clicking on appropriate responses (for text), or entering numeric values. A context sensitive help facility allows access to additional information when the user has difficulty understanding a question or deciding on an answer.*

*The major functionality of PACES is to act as a knowledge rich system which includes block diagrams, text, and graphics, linked using hypermedia techniques. This allows easy movement among pieces of the knowledge. Considerable documentation of the spacecraft*

*Power and Attitude Control Subsystems is embedded within PACES.*

*PACES is being designed and will be delivered on a Macintosh II computer using NEXPERT OBJECT from Neuron Data as the expert system shell. The graphics oriented user interface to NEXPERT is constructed with AI Vision, a graphics interface tool also from Neuron Data.*

*The development phase of TDRSS expert system technology is intended to provide NASA (Code 405) the necessary expertise and capability to define requirements, evaluate proposals and monitor the development progress of a highly competent expert system for NASA's Tracking and Data Relay Satellite Program.*

## **Introduction**

The Power and Attitude Control Expert System (PACES) for the Tracking and Data Relay Satellites (TDRS) is intended to assist spacecraft engineers in diagnosing anomalies both on-orbit, and during integration and testing (I&T) of the spacecraft. It is also to be a "knowledge rich" system or information repository, providing engineering explanations of how TDRS Power and Attitude Control Subsystems (ACS) function.

## Goals

The major goal of building TDRS PACES is to provide NASA Code 405 personnel with the expertise in actually building a fieldable expert system. This first-hand experience will allow NASA personnel to better judge the expert system components of proposals, and to be more knowledgeable in monitoring and managing expert system projects.

Achieving the primary goal requires actually building a system. Therefore, a prototype (MOORE) was developed, which demonstrated the concept of a diagnostic system. TDRS PACES is currently under development with the goal of being a system which can be implemented. Therefore, it must contain sufficient information to do useful work, and present that information in a usable format.

## Objectives

To meet these design goals, TDRS PACES has the following objectives:

- Capture diagnostic knowledge of Power and ACS subsystems, sufficient to allow identification of the most likely component failure at a level which would allow switching to redundant circuitry.
- Maintain information on failed components and anomalies of each spacecraft so that advice can be tailored to the unique characteristics of each satellite.
- Capture block function diagrams, schematics, and illustrations of physical spacecraft components for use by spacecraft engineers.
- Integrate diagrams with each other so engineers can move between the types of representation and levels of detail.
- Integrate the diagrams with TDRS PACES in such a way that the diagnostic function provides initial access to the most appropriate diagram for any identified fault.

- Provide NASA Code 405 personnel with sufficient experience in building expert systems so they can specify their requirements in requests for proposals, evaluate proposals, and judge the quality of expert systems built by contractors.
- Build a system of sufficient complexity and ease-of-use to demonstrate the effective integration of expert system technology in daily orbital operations and test activities. (NASA 88)

## Hardware and Software

TDRS PACES is being built using two Apple Macintosh IIs with nineteen-inch color monitors. Each machine has eight megabytes of RAM and a 100 megabyte hard disk. The Macintosh was chosen because of its graphics interface, ease-of-use, and consistent operation across applications. It was also seen as an economical alternative to much costlier workstations. Two machines were used to allow parallel development of portions of the expert system. The large amount of RAM and disk storage were chosen to insure the availability of adequate memory.

The expert system was built using Neuron Data's *NEXPERT OBJECT*. NEXPERT runs on multiple platforms, all of which are general-purpose computers. It includes both rules and an object system – allowing for flexibility in design, and built-in access to external databases. A parallel product from Neuron Data, AIVision, is being used to create a graphical user interface.

A New Image Technology flat bed scanner with associated software, is being used to input some of the graphics to TDRS PACES. Other images are created using several graphic packages, most notably Cricket Draw, Aldus FreeHand, and Adobe Illustrator. Laser writer output of graphics and screen dumps are used with our attitude control expert to eliminate shipping the computer equipment for some of the knowledge acquisition sessions. Shipment of computer resources is necessary because of the remote location of one of our experts.

## **Situation**

Creating an expert system to aid in diagnosing spacecraft anomalies is a difficult task. On the one hand, only a limited number of actions are possible. On the other, it is desirable to know which specific component failed and why. Such knowledge allows corrective action to be taken on future spacecraft, and assessment of risks associated with future performance. A conservative approach must be used when taking action to correct faults as irreparable damage could result if the wrong measure is attempted.

TDRS PACES will operate in the diagnostic process as a consultant. The expert system will not make any decisions for the spacecraft engineers. Rather, it will function as a source of information and advice. TDRS PACES is designed to be used by ground support spacecraft engineers, and by spacecraft engineers during integration and testing of the spacecraft.

### **Loss of Expertise**

There are several characteristics of TDRS diagnostics which suggest the use of expert systems technology. The spacecraft are being built over a prolonged period of time, and they will be used for many years. This means that there will continue to be losses of expertise due to personnel changes. New personnel will need to acquaint themselves with the TDRS satellites.

Each TDRS is designed to have a shelf life of seven years, and a total active life, including storage of eleven years. Since flight 7 is being built now, it is possible that one or more of the satellites will still be used in the year 2000.

At the same time, several key TDRS engineers are nearing retirement. Their expertise will be unavailable in later stages of TDRS operations. Many remaining personnel transfer to other programs as the major work of building the satellites ceases. Without means of capturing engineering expertise specific to the TDRS system, diagnosing faults and suggesting remedies for spacecraft

incidents will become increasingly difficult as time passes.

The satellites are being built in an overlapping fashion. At the time Flight 4 was being packaged for shipment to Cape Canaveral, the bus and payload had been mated for Flight 5, while Flight 6 was still in early I&T because many of its modules were used as replacements on Flights 3 to 5.

Only three spacecraft will be on-orbit at any one time: two operational, one as a spare. Other spacecraft will be stored after assembly. In the future, they will be brought out of storage as needed. Currently under construction is Flight 7, a replacement for Flight 2, which was lost with Challenger. Much of the expertise which was available during initial I&T is likely to be unavailable for I&T of Flight 7, or when a satellite is brought out of storage and tested after several years.

Once again, capturing the expertise which is available now will make it easier to deal with gremlins which crept in to a spacecraft while it was being stored. This same expertise will help with the I&T of Flight 7, a task on which there are several engineers unfamiliar with TDRS.

### **On-orbit Problems**

Making repairs to on-orbit spacecraft is a rather limited process. All test data must be collected from telemetry points which were determined during system design. The only repairs which can be affected involve the use of redundant components. Again, all redundancies were part of initial system design.

Because of the limited capacity for on-orbit repairs, satellites are built to be extremely reliable. Thus, relatively few on-orbit problems have been experienced. More difficulties were experienced in the integration and testing phase of the satellites. This I&T data provides some basis for case histories, but the number of faults in I&T is still limited.

Having few problems to comprise an historical record results in limited data from actual cases from which to gather diagnostic expertise. Thus, one must go to the models on which the spacecraft were built to diagnose new faults.

## **Beyond the Prototype**

In 1987-88, a prototype expert system was constructed (Howlin, Weissert, & Krantz 88) to demonstrate the concept of applying expert system technology to diagnosing on-orbit problems in TDRS. The expert system was called MOORE after Mr. Bob Moore, TRW, Redondo Beach, CA, whose expertise was captured in the system. Mr. Moore continues to serve as an expert for TDRS PACES.

The scope of TDRS PACES is wider than MOORE, and it has different objectives. While MOORE was a demonstration prototype, TDRS PACES is designed to be expandable into an implemented system. Different tools are being used, as well as a different approach.

### **Different Objectives**

MOORE was designed from the start to be a demonstration prototype. It illustrated that Artificial Intelligence concepts could be applied to the diagnosis of on-orbit incidents for TDRS. It generated interest in AI technology, and enabled funding of a development system.

TDRS PACES is designed to be a deployed system. Therefore, it must contain sufficient expertise for it to be useful to spacecraft engineers in diagnosing actual on-orbit problems.

### **Case-based vs Model-based**

MOORE was based on reports of on-orbit problems with TDRS Flight 1. Thus, MOORE was at heart a case-based system. In addition to handling exact cases which actually occurred, MOORE was extended slightly to cover problems which were substantially the same as those actually experienced.

There are two major limitations to the case-based approach. First, the number of on-orbit problems is extremely small. Only about 70 anomaly reports were logged over a five year period. These reports covered all aspects of spacecraft operation. Only a small percentage of these were related to ACS difficulties, the only area addressed by MOORE.

The second limitation involves making up problems or playing "what-if..." games. Hypothetical problems could serve as a basis for some expert systems, but not with TDRS. The satellite has many assemblies with thousands of piece-parts each. Hypothesizing could go on for many years, not be inclusive, and produce a system that would be too unwieldy to be implemented. The case approach also yields diagnoses which are much more specific than can be corrected in orbiting spacecraft.

We have chosen a model-based approach for the current expert system. TDRS PACES is based on models of how the power and attitude control subsystems operate, rather than on actual cases. TDRS PACES will provide diagnoses only to the level of replaceable components or redundancies. Then, it will provide a spacecraft engineer access to schematics, function diagrams, and textual information which can aid the engineer in making a more detailed diagnosis of the problem.

### **Expanded Scope**

MOORE was concerned with diagnosing on-orbit Attitude Control Subsystem problems. TDRS PACES expands that scope in several ways. While TDRS PACES will not have the depth of MOORE, it will have considerably more breadth.

TDRS PACES contains information about the Power Subsystem. Mr. Al Gillis, NASA Code 405, GSFC, will serve as the expert for the Power Subsystem. Power would have been a particularly difficult area for using a case-based approach as there have been no power anomalies with Flight 1.

MOORE was designed to serve as a diagnostic system only. In addition to diagnostics, TDRS PACES has an integrated exploration or teaching component. Since many of the spacecraft engineers who could be diagnosing problems with a satellite may have little knowledge of the specific spacecraft, a knowledge intensive component was considered to be essential to an implemented system.

Flight 7 is still to be built and tested, and Flights 5 and 6 must be retested when they are removed from storage. So, TDRS PACES will include information about integration and testing. Including expertise about I&T activities makes TDRS PACES more generally useful.

## Interfaces

TDRS PACES uses the interface tools provided by NEXPERT and AIVision for most of the interaction with users. User prompts, graphic interaction, and database accesses are all provided. Where these tools prove inadequate, they are supplemented with routines written in C. The C routines are compiled into the module which makes the NEXPERT library calls. This integration of external routines is an integral feature of NEXPERT.

TDRS PACES will interface with the Reliability Analysis Report database. This interface will allow the engineer to gain access to historical information on the functioning of the spacecraft. The information from the database will be requested by a set of pre-planned queries. The engineer will be presented with options, allowing the selection of pertinent information on a specific spacecraft, or for all spacecraft. The returned data will be reflected to the user through pop-up windows. At this point, the engineer will be able to review the data to determine whether a similarity exists between one of the previous anomalies and the current problem.

The expert system is designed to be used by spacecraft engineers, not software specialists. Therefore, a help facility is being provided

which will allow for clarification for questions asked by the system by providing additional explanatory information. In some cases, instructions for moving from one screen to another are provided. Selecting the "WHY" option from the menu in dialog boxes, or clicking on the "HELP" button in graphic displays presents the additional information.

For the majority of interaction with the system, TDRS PACES makes use of the built-in functionality of NEXPERT *OBJECT*. NEXPERT includes a dialog window which prompts the user for answers. AIVision allows for the creation of screens which can display information, and have "hot" areas. These areas can lead to other screens, convey information back to the NEXPERT inference engine, or display the values of objects within NEXPERT. NEXPERT also provides options for allowing text and graphics windows to be opened, displaying static information.

The AIVision screens are used to display graphics, diagrams, and text; providing hypermedia facilities. The dialog window is used to obtain answers to questions. As TDRS PACES grows, some of the dialogs will be replaced by AIVision screens. In other cases, the AIVision screens will contain variable information – information which may be different for each spacecraft.

## Diagnostics

Performing diagnostics for the satellites is one of the two main functions of TDRS PACES. The diagnostic system will be built to include both on-orbit and I&T anomalies. All recommendations of the expert system are purely advisory. Spacecraft engineers retain full control over all corrective actions.

Two different types of diagnostics are required by spacecraft engineers in the diagnosis of on-orbit problems. At the action level, a diagnosis is required which will fix the problem – i.e. put or keep the spacecraft on-line, passing messages back and forth between other spacecraft and the White Sands Ground Terminal. In addition, the engineers must determine the exact component which failed. Individual components are not replaceable.

Identifying the failed part is a “deep” problem compared to the “shallow” problem of finding the failed assembly or subassembly of which the failed component is a part.

The shallow knowledge represents a much smaller body of knowledge than the deep knowledge. It is possible to identify and represent this shallow knowledge in a reasonable length of time.

## System Structure

Mr. Moore, the attitude control expert begins the diagnostic process by asking a standard set of questions. This set of questions is used as the introduction to the diagnostic phase of TDRS PACES. The attitude control questions are supplemented with questions about the time of year to gain initial information about the Power Subsystem. Because the spacecraft is eclipsed by the earth for short periods of each day in the fall and spring, different operations related to charging and using the batteries are performed before and during these eclipse periods.

The initial questions for on-orbit satellites, along with the selectable responses in brackets, include:

- Which spacecraft is experiencing problems? [F1, F3, F4]

- On what day did the error occur (DD-MM-YY)?
- At what time did the error occur (HH:MM:SS)?
- Is this a valid spacecraft event? [Yes, No]
- Is the spacecraft in fail-safe mode? [Yes, No]
- In what mode of operation was the spacecraft when the problem was experienced? [Earth, Inertial, Normal, Sun]
- What function were you performing when the problem was first noticed? [Antenna Slew, Momentum Dump, Monitoring, ...]

Figure 1 illustrates the three types of dialog window provided by NEXPERT. They allow entry of boolean values, selection from a list of choices, and entry of text or numeric data. The default screens are used in all cases where they are not superseded by a specific graphic screen.

Diagnostic fault trees are constructed for each redundancy. The trees specify path(s) leading to the diagnosis of a problem with the (sub)assembly. When a (sub)assembly is found to be at fault, the recommended action includes switching to the redundant (sub)assembly. The fault trees are implemented as production rules.

**Figure 1. Default response screens.** There are three default response screens provided by NEXPERT. The one on the left allows entry of numeric values from the keyboard. The middle one allows for response to “Yes/No” questions. For text strings, NEXPERT presents all possibilities in a scrollable list as in the box at right. In all cases, an option is provided for the user to indicate “Not Known” – a response which can be used to bring up other questions.

Assemblies and subassemblies are considered to be objects in TDRS PACES. Separate objects are maintained for each satellite to allow recording failed components in specific spacecraft. The level of modeling extends to where components have redundancies. The objects are grouped into classes.

Data which form the objects are kept in external database files for easy updating. When TDRS PACES is run, objects are created from the latest data.

## Exploration

Perhaps the most important feature of TDRS PACES will prove to be the exploration facility. While the exploration function contains no complex reasoning, it provides the type of information which a spacecraft engineer will need in order to understand the Power and Attitude Control Subsystems of TDRS. The exploration facility is designed to be relatively large and extensible.

The exploration facility contains schematics, function diagrams, textual descriptions, and illustrations of spacecraft components. They are linked by "hot spots" - areas on the screen which when clicked on, bring up other screens.

Two types of linkages are available. Within a type of screen, similar screens with greater or lesser detail can be accessed. A screen of one type also allows access to other types of screens - other presentations of the same material.

Figure 2 contains sample screens, illustrating their linkages. A diagram of the attitude control sensors and actuators will connect to more detailed diagrams of the sensors and actuators. By clicking the "hot spot" on a reaction wheel assembly in the sensors and actuators diagram, a graphic of the reaction wheels is presented. Then, clicking on the Function button brings up a text description of the reaction wheels. From the graphic of sensors and actuators, one can gain direct access to the function block diagram or an overall text description of the ACS.

The information contained in the Exploration facility comes from briefings and project documents. The briefings were given by Mr. Bob Moore and Al Gillis over several years and represent information they deem to be important. This briefing material is supplemented by information obtained from Messrs. Moore and Gillis in knowledge acquisition sessions. The primary document used for obtaining graphics and explanatory information is *The TDRSS Spacecraft Systems Manual* (TRW 85). Graphics were entered through drawing programs or by using an image scanner.

## Conclusions

Through the process of building TDRS PACES, Code 405 is gaining considerable experience with the practical aspects of developing, managing, and monitoring an expert system project. This experience will prove to be of considerable value as more projects contain requirements for including expert systems.

In many respects, TDRS PACES reflects the experience of many real-world systems regarding actual artificial intelligence content. The most useful feature of the system is the knowledge-rich, hypermedia section. While this contains much information and expertise, that expertise is captured in the graphic interface, not in the inferencing process. However, it is important to remember that TDRS PACES is designed to do useful work - work which saves time and money - not to break new ground in theoretical areas.

## References

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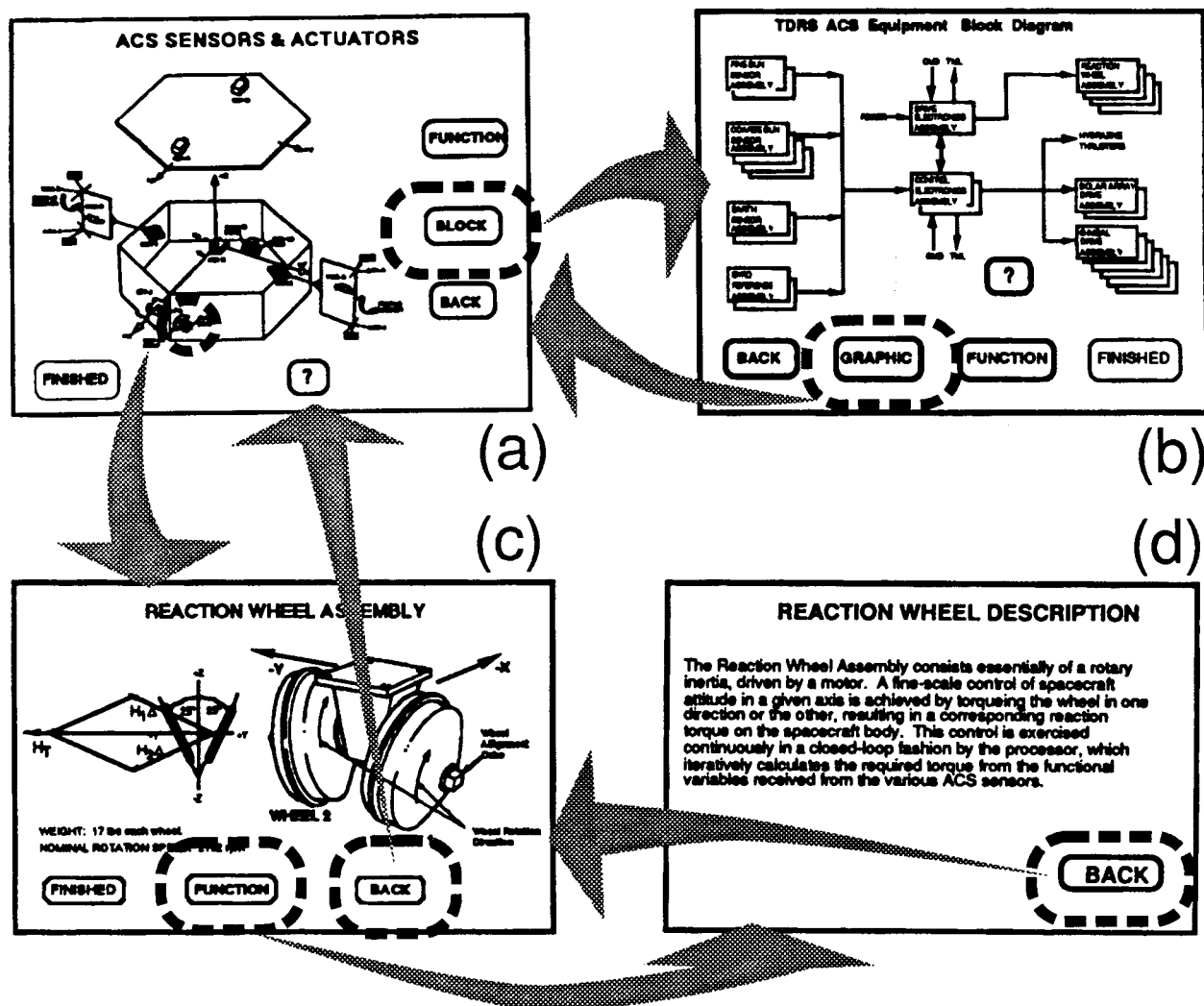
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**Figure 2. Types of exploration screens and their linkages.** From a graphic of the ACS sensors and actuators (a), clicking on the "Block" button brings us a block diagram of the ACS system (b). Clicking on the "Graphic" button on the block diagram, brings up the graphic of the system. Clicking on the reaction wheel section of the ACS Graphic (a), brings up a detailed graphic of the reaction wheels (c). Selecting the "Function" button brings up a textual description of the reaction wheels (d).